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Decarbonization strategies for northern Canada: A review of renewable energy and energy storage in off-grid communities

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ABSTRACT

This study explores the challenges and opportunities of decarbonizing isolated communities in northern Canada, which heavily rely on fossil fuels like diesel, contributing to significant greenhouse gas emissions. It examines renewable energy options, including wind, solar, and hydro, and identifies the technical, geographical, and social barriers to their implementation. Wind power, especially effective in the north, can reduce diesel dependence when combined with hybrid systems. Solar power complements other sources but is limited in winter. Hydropower remains essential but is constrained by geographical and environmental factors. The study also addresses energy storage technologies to ensure stable energy production. Thermal energy storage, including borehole and rock-pile systems, stands out for its efficiency, even in extreme climate conditions. Compressed-air storage offers a long-term solution, though its high initial cost is a challenge. Pumped hydro storage is effective but relies on natural landforms or costly infrastructure investments. Lithium-ion batteries are useful in reducing fossil fuel dependence but underperform in extreme cold, and their high cost remains an obstacle. Flywheels, though not suitable for primary storage, can provide fast, auxiliary storage to batteries. Hydrogen, despite its cost, is a promising option for large-scale, long-term storage. Finally, integrating indigenous communities into energy management is crucial to ensure that projects respect local traditions and are sustainable. The most effective approach combines multiple energy production and storage technologies tailored to each community's specific needs. This study lays the groundwork for future projects to decarbonize northern Canada's isolated communities with sustainable and locally adapted energy solutions.

Introduction

In September 2011, the United Nations General Assembly launched the "Sustainable Energy for All" initiative to provide everyone with sustainable energy access by 2030 [1]. Sustainable energy is achieved when energy is readily and reliably available at an affordable cost and can be used efficiently and effectively for all essential needs without causing long-term negative impacts on society [2]. The Arctic region includes nearly 1,500 off-grid communities, home to over 1.6 million people across Canada, the United States, Russia, Norway, and Denmark, which remain far from achieving a sustainable energy system [3]. These communities face critical challenges related to energy supply and climate change, challenges expected to intensify in the future.

Indigenous and Northern Affairs Canada defines off-grid communities as "permanent or long-term settlements (five years or more) consisting of at least 10 permanent buildings, not connected to the provincial electricity grid or the natural gas network" [4]. In Canada alone, there are approximately 280 such communities, including both Indigenous and non-Indigenous settlements, such as villages, small towns, mining camps, and other camps supporting long-term

Abbreviations: BTES, Borehole thermal energy storage; CAES, Compressed air energy storage; FES, Flywheel energy storage; GHG, Greenhouse gas; PHES, Pumped hydroenergy storage; PTES, Pumped thermal energy storage; RPTES, Rock piles thermal energy storage.

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commercial operations (e.g., forestry and fishing) [5]. For all these communities, energy supply is a shared challenge. As shown in Fig. 1, a significant portion of these communities rely on fossil fuel-based electricity generation, with over 80 % dependent on diesel generators [4,6].

The typical configuration of a microgrid generally includes several large diesel generators to meet electricity demand, with one or more additional generators kept on standby to handle demand peaks [9,10]. For the remaining 20 % of off-grid communities, diesel generators remain a key component of electricity production, serving either as a backup power source or as a means to balance the load when energy from alternative sources like wind, solar, hydropower, or biomass is insufficient or unavailable [4].

While diesel generators have low capital costs and ensure high electrical reliability, electricity costs in remote areas remain extremely high due to elevated fuel prices and the substantial expenses associated with fuel transportation and storage [11]. The recurring transport of goods, including fuel, to these isolated regions is less frequent than in non-remote areas, and it faces additional environmental challenges such as long distances, difficult access, and harsh conditions. These factors significantly increase shipping costs [12], directly impacting energy supply expenses. For instance, electricity costs in remote Canadian communities can be exorbitant, reaching up to $1.14/kWh in some regions, ten times higher than the average rates of $0.10 to $0.15/kWh paid by most Canadians [13]. Beyond financial costs, another drawback of this heavy reliance on fossil fuels is the environmental impact on communities caused by greenhouse gas emissions and other pollutants associated with diesel use [14].

In addition to the inherent isolation of these communities, the climate poses another significant challenge. These communities are located in subarctic to arctic climates. Fig. 2 shows a map of heating degree-days below 18 °C in Canada for the 1951–2010 period (the black dots represent the meteorological stations used to create this map).

Buildings in these communities require heating for a significant portion of the year, with an average of approximately 8,000 heating degree-days below 18 °C [16,17]. This heating is typically achieved using domestic oil-fired boilers [18]. Notably, heating consumes roughly three times more fossil fuel than electricity generation in northern Canadian communities [19].

To achieve the United Nations General Assembly's 2030 goal and contribute to meeting the Paris Agreement's target of limiting global warming to 1.5 °C by 2100, it is essential to increase the capacity of renewable energy technologies installed in these isolated regions [20]. The mining sector also plays a pivotal role in this effort. Consuming a significant portion of Canada's total industrial energy (1,439 PJ in 2020, according to Natural Resources Canada [21]), the Canadian mining industry is responsible for approximately 47 % of the country's industrial greenhouse gas emissions [21]. This carbon dependency is even more pronounced in remote mines, where the lack of access to electricity grids and natural gas pipelines makes them entirely reliant on fossil fuels for energy needs, including electricity, transportation, and heating. Given the scale of these carbon emissions, the mining sector has been actively seeking innovative solutions to decouple its energy supply from fossil fuels, with some efforts aiming for complete decarbonization in recent years [22,23]. Over the past few decades, several projects have explored the potential of renewable energy sources in these communities [24,25]. However, their intermittency characterizes renewable sources like wind and solar. Windless days or cloudy weather can lead to reduced energy output, while certain periods may produce unused energy surpluses. As a result, this energy transition must necessarily include implementing storage solutions. However, the technical, economic, and environmental constraints specific to these remote regions are complex and difficult to extrapolate from conventional application scenarios.

To date, no scientific publication has jointly addressed the integration of renewable energy and energy storage in off-grid communities of Northern Canada. Although each of these dimensions has been the subject of research when considered independently, their combined application in this specific geographic and socio-economic context remains largely unexplored. This gap is particularly significant given that these communities — predominantly Indigenous and highly dependent on fossil fuels — exhibit unique energy consumption profiles and are exposed to extreme climatic conditions. An integrated approach that simultaneously considers renewable energy production and energy storage in these settings would not only fill a critical gap in the literature but also support the development of concrete strategies for a just, sustainable, and context-appropriate energy transition in northern regions. This review addresses this gap by cataloging the different renewable energy sources available in these regions and exploring the energy storage solutions commonly used. It explicitly examines their performance from energy, economic, and social perspectives, highlighting the issues associated with their installation. The second part of this review

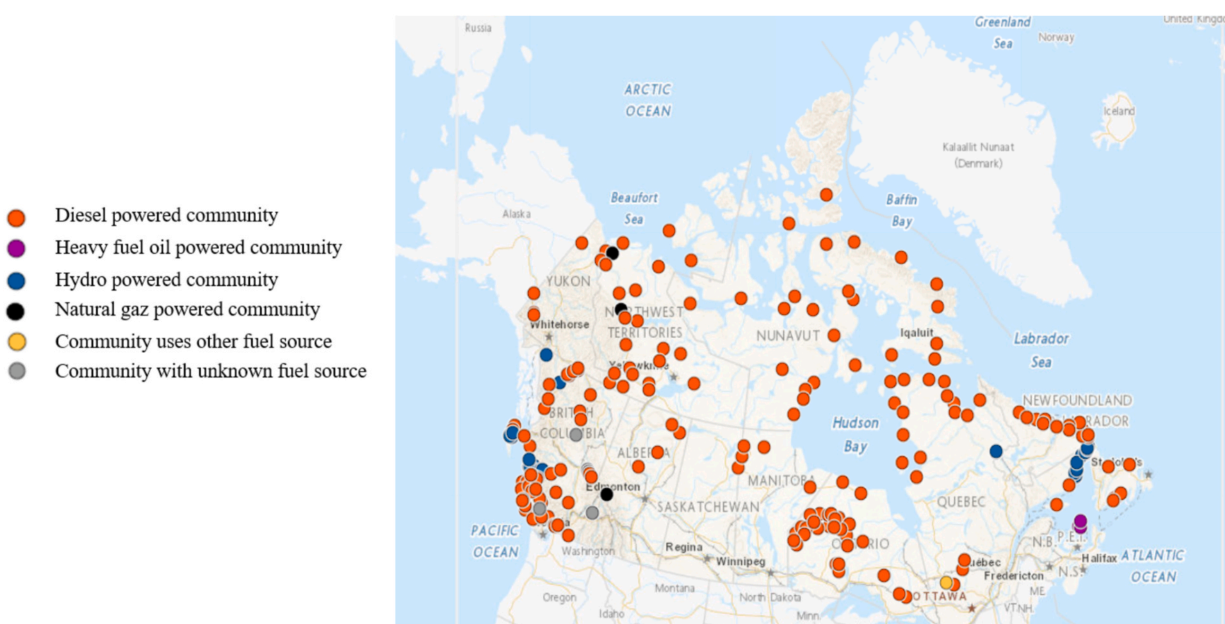

Fig. 1. Isolated communities in Canada and their energy [,]
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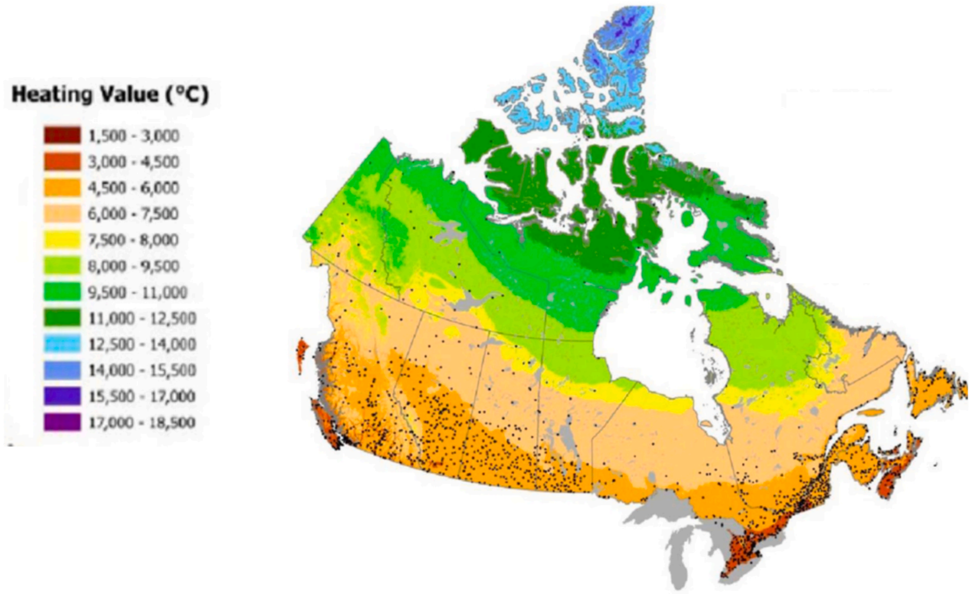


Fig. 2. Heating degree-days below 18 °C for the 1951–2010 period [15].

focuses on the available and commonly used renewable energy sources, while the third concentrates on storage solutions. Although the analysis is rooted in the Canadian context, the results and conclusions have broader relevance. They can indeed be applied to other off-grid northern communities, such as those in Alaska, Greenland, or certain regions of Russia, which share similar energy, climatic, and socio-economic conditions.

1. Renewable energy sources for electricity generation

Remote communities in Canada face unique energy challenges due to their reliance on expensive and environmentally harmful diesel fuel for electricity generation and heating. However, these communities have significant potential to integrate renewable energy technologies such as wind, solar, hydropower, geothermal, and biomass. This integration could reduce dependence on diesel, lower costs, enhance energy security, and decrease greenhouse gas emissions. For instance, Stringer and Joanis [26] estimated the cost of decarbonizing 148 off-grid microgrids in Canada. Using an optimization model and data on wind, solar radiation, and future costs of generation technologies (wind turbines and photovoltaic panels) and storage solutions (lithium-ion batteries and vanadium flow batteries), they identified the most cost-effective solutions for each community by 2050. The results show that wind turbines are currently the most economical option, but solar panels will become more cost-effective in the future. However, the transition to renewable energy is not straightforward and is subject to several challenges.

1.1. Constraints and challenges

It is important to note that completely eliminating the use and importation of diesel in these communities does not seem feasible, primarily for safety reasons. Indeed, the intermittency of renewable energy sources, potential failures, or maintenance shutdowns make it essential to have generators available when needed. Studies have shown that hybrid renewable-diesel systems with a renewable energy share of 21 % to 80 % offer a good balance between cost and emission reduction compared to diesel-only generation [27].

Nwanekezie et al. [28] conducted a strategic assessment of the energy transition to renewable sources in Saskatchewan, focusing on opportunities, risks, and economic impacts. Their study highlighted concrete strategies for ensuring an effective transition and achieving future electricity production goals, particularly for isolated communities. This research provided implementation pathways to ensure a sustainable and reliable energy system. They noted that the transition to renewable energy is not limited to developing projects in this field; it is primarily a political and institutional struggle that challenges well-established norms and relationships. Furthermore, Stefanelli et al. [29] suggested that Indigenous communities should be involved in decision-making processes and ownership of renewable energy and energy autonomy projects. Since the deployment of technologies falls under provincial jurisdiction, Indigenous involvement should include their leadership, motivations, partnerships, and/or participation in the renewable energy sector to create more reliable energy systems, increase their autonomy, and generate long-term financial benefits.

Mercer et al. [30] studied the barriers to the transition to renewable energy through a case study on wind energy development in Newfoundland and Labrador. The study revealed that there is no single barrier to the development of renewable energy sources, and it proposed policy solutions to support the wind energy development plan. Hoicka et al. [31] surveyed the involvement of Indigenous communities in Canada's energy transition. The study identified 41 renewable energy projects controlled by Indigenous communities and suggested that support for equitable ownership and comprehensive policies would strengthen the focus on community development.

The geographical isolation of northern communities and extreme climatic conditions pose a major obstacle to integrating renewable energy. Several factors hinder this process, including the need to transport equipment to installation sites, which can be costly and involve complex logistics, as well as the impact of extreme weather conditions on the accelerated deterioration of equipment. Furthermore, these conditions make technical interventions in the event of a breakdown particularly difficult and sometimes dangerous. However, public policies and local community initiatives are crucial beyond these technical and environmental challenges. Political decisions, institutional support, and the active involvement of local populations are essential to overcome these obstacles and ensure the long-term success of renewable energy projects in these remote regions [32].

Canada's current energy policies play a critical role in accelerating the energy transition of off-grid communities, notably through the implementation of carbon pricing systems and the development of targeted incentive measures. Trading systems for large emitters, enshrined in legislation, alone account for an estimated 20 % to 48 % of the projected emission reductions by 2030 [33]. These systems impose a cost on industrial emissions while safeguarding the competitiveness of key sectors. In parallel, fuel charges encourage households and businesses to adopt cleaner energy sources. Together, these mechanisms create a supportive framework for the integration of renewable energy in remote communities.

However, several regulatory barriers remain. On the one hand, counterproductive policy interactions—such as the oversupply of carbon credits in certain markets—can dilute the incentive effect of cap-and-trade systems. On the other hand, the lack of coordination across levels of government and the failure to adequately address northern-specific challenges limit the direct impact of these policies on remote communities.

To overcome these constraints, it is essential to tighten emission intensity standards, improve intergovernmental harmonization, and explicitly integrate the realities of northern regions into national policy frameworks. Ultimately, the effectiveness of the energy transition in off-grid areas will depend not only on the continuation of existing measures but also on their adaptation to the structural and geographic constraints unique to these territories.

1.2. Renewable energy sources in Canadian off-Grid communities

Barrington-Leigh and Ouliaris [34] analyzed the renewable energy landscape in Canada. The study relied on national population density to examine renewable energy's supply, development, and expansion. The results indicate that renewable energy technologies can be deployed, with two-thirds of the energy coming from onshore and offshore wind and the rest from hydroelectricity. However, this study is not explicitly focused on isolated communities; on the contrary, it prioritizes locations close to areas with high population densities.

Karanasios and Parker [35] studied the energy transition by tracking the deployment of renewable electricity in remote Indigenous communities in Canada. The results show that from 1980 to 2016, seventy-one renewable energy projects were implemented in remote communities (Yukon, Northwest Territories, British Columbia, and Ontario). The transfer of ownership and active participation of Indigenous communities helped support the energy transition, economic development, and benefits related to self-governance. According to Agu et al. [36], between 2010 and 2021, 635 renewable energy projects with a capacity of 28,000 MW were deployed in remote communities in Canada. Table 1 lists the number of renewable energy technology projects deployed (in operation) in remote communities in Canada between 2010 and 2021 by type of renewable energy.

Wind and solar projects dominate the renewable energy landscape in remote Canadian communities, followed by hydroelectric and biomass projects. Data reveals that Ontario has the largest number of wind and solar projects, followed by Nova Scotia and Alberta. For example, a case study in the Kasabonika Lake First Nation community in Ontario found that photovoltaic solar and wind energy could reduce greenhouse gas emissions by 3.5 % to 6.2 % [39]. British Columbia, on the other hand, has the most hydroelectric projects. Regarding biomass-related projects, the number is nearly equal in British Columbia and Ontario.

Table 1
Number of renewable energy technology projects deployed in Canada's remote communities between 2010 and 2021 [31,36–38].

Provinces and territories	Wind	Solar	Hydro	Biomass
Alberta	17	19	0	6
British Columbia	13	3	50	23
Manitoba	2	1	1	0
New Brunswick	7	0	0	3
Newfoundland and Labrador	1	0	0	1
Northwest Territories	1	2	2	0
Nova Scotia	72	2	0	2
Nunavut	0	2	0	0
Ontario	93	174	26	22
Prince Edward Island	2	1	0	0
Quebec	42	4	14	8
Saskatchewan	7	6	0	2
Yukon	0	2	2	0
Total	257	216	95	67

1.2.1. Wind power

Wind energy is a common source of electricity generation and plays a key role in the global energy market. Wind is an inexhaustible and free resource available in many regions of the world. According to McCarney et al. [40], wind energy is Canada's least expensive source of new electricity generation capacity.

Fig. 3 shows the map of average wind speeds at 100 m height for all of Canada.

This map highlights Canada's wind potential, showing that wind speeds in most regions of the country generally exceed 5 m/s. It also supports the information presented in Table 1, where it is observed that wind energy projects are particularly numerous in Ontario, Nova Scotia, and Quebec. Furthermore, the map identifies areas with high wind potential for isolated communities in northern Quebec, Nunavut, and the Northwest Territories, where wind speeds can reach up to 9 m/s, offering opportunities for the development of wind energy in these remote regions.

According to a study by Weis and Ilinca [42], in Canada, 89 villages have wind speeds of at least 5.0 m/s, suggesting potential for future wind energy projects in these remote areas. However, the authors note that only 10 of these villages are economically viable for wind-diesel hybrid systems without financial support. By introducing an incentive of $0.15/kWh, this number could increase to 62. If projects are realistically deployed, about half of these villages could benefit from wind energy in the next decade. The installation cost of wind turbines has been estimated at between CAD 5,000/kW and 6,000/kW. The Diavik diamond mine, located in the Northwest Territories, is the first mine in Canada to integrate renewable energy into its power supply. Since 2012, four 2.3 MW wind turbines have been gradually installed to provide 10 % of the mine's energy needs. Despite a high initial cost (CAD 31 million), the wind energy system reportedly replaced 3.8 million liters of diesel in 2013 [43]. Inspired by Diavik's success, the Raglan nickel mine in northern Quebec built a 6 MW wind farm in 2015 to meet 10 % of the mine's energy requirements. It is reported that the renewable system saves 4.4 million liters of diesel annually, reduces carbon emissions by 12,000 tons, and eliminates the equivalent of emissions from 2,700 vehicles on the road [44]. Furthermore, several studies show that using wind energy, coupled with storage devices, provides a stable and constant energy source throughout the year, especially in remote areas where wind is an abundant resource [45].

Indeed, the wind potential in these regions is promising, but it faces significant technical and material challenges due to geographic isolation and harsh climatic conditions. First, icing presents a major challenge: it can alter the aerodynamics of wind turbine blades, reducing their efficiency while increasing structural loads [46]. Furthermore, ice can disrupt critical sensors necessary for optimizing performance and ensuring the safety of installations. While solutions exist, such as active de-icing systems (using heat or chemical liquids) and passive systems (like hydrophobic coatings), these technologies come with significant additional costs during installation [47]. Geographic isolation is another major obstacle. These regions often lack the necessary infrastructure, such as roads or ports, to transport and install bulky, heavy components. Moreover, installing wind turbines can have a notable ecological impact, particularly by disturbing the natural habitats of local wildlife, including birds [48], which can pose a problem for Indigenous communities that place a high value on environmental preservation. These combined factors make wind energy development in these isolated regions complex and costly, requiring tailored solutions, careful planning, and the involvement of local communities.

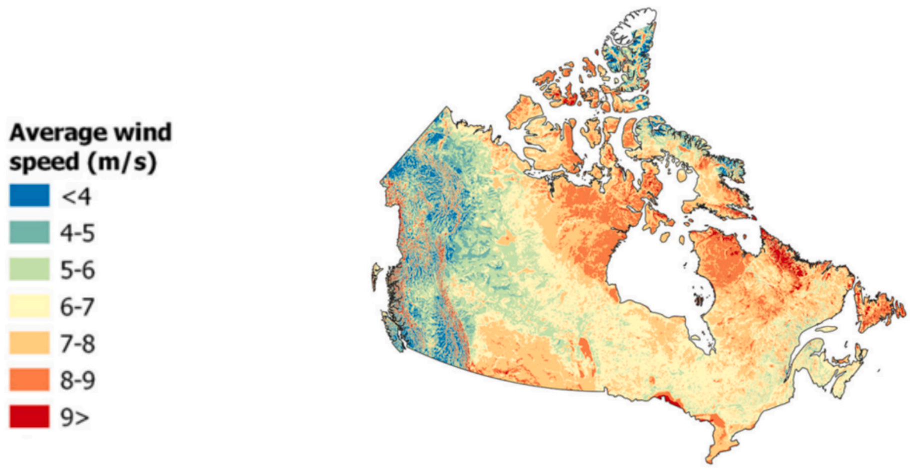


Fig. 3. Map of average wind speeds at 100 m height for all of Canada [41].

1.2.2. Solar power

Solar energy is radiant electromagnetic wave energy coming directly from the sun. Technologies and processes have been developed and applied to collect and use this energy. In photovoltaic solar panels, a set of solar cells converts light energy into electrical energy. The amount of energy produced per day depends on factors such as the surface area of the solar panels, their geographic location, local shading, and their orientation [49].

Fig. 4 presents the solar potential map, in kWh/kW installed across Canada, determined for south-facing photovoltaic panels.

This map illustrates Canada's solar potential, with values reaching between 1300 and 1400 kWh/kW in the most favorable regions in the south. However, solar potential decreases significantly in the northern regions of Canada, which partly explains the limited deployment of this technology in provinces such as Nunavut, the Northwest Territories, Yukon, and northern Quebec, as shown in Table 1. In contrast, these data highlight the increased importance of solar projects in Ontario, where the potential is much higher. Since many isolated communities are located in northern Canada, the solar potential there is less attractive than wind energy.

One of the main drawbacks of solar energy is the temporal mismatch between its availability and the energy needs of communities. Indeed, the peak energy demand occurs in winter, precisely when solar energy availability is at its lowest. Therefore, to fully harness the potential of this resource, it is ideal to implement seasonal energy storage systems, which allow energy produced during periods of high availability, such as summer, to be stored and redistributed in winter when demand is at its peak. The main factors limiting photovoltaic production include reduced solar resource intensity, losses due to spectral imbalance, snow coverage, losses due to soiling, increased sensitivity to temperature, and risks of structural damage [50–54]. Power electronic components, wiring, and the foundations supporting these panels must also withstand freezing, icing, and thawing of permafrost, as well as significant daily temperature fluctuations [55–57].

Despite these challenges, several studies have explored integrating solar energy as a power source in isolated communities [45,46]. However, it is typically not used as the sole energy source but rather in combination with other forms of energy, such as diesel, wind, or biomass, to meet energy needs more quickly and flexibly.

1.2.3. Other energy sources

Solar and wind resources are the main renewable energy sources studied and utilized in isolated regions due to their high potential and relative availability in several areas of Canada. These two resources have been the subject of extensive research and analysis to assess their performance, technical feasibility, and environmental impact. However, they are not the only resources of interest. Other renewable energy sources, such as biomass and small-scale hydropower, have also been

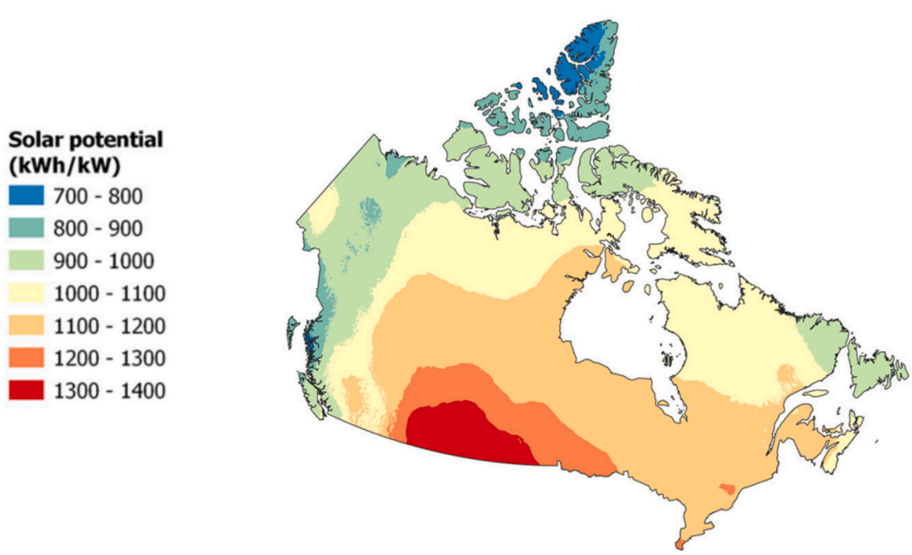


Fig. 4. Solar potential map across Canada, determined for south-facing photovoltaic panels [41].

examined in various studies. These research efforts aim to explore complementary or alternative solutions to diversify energy options and meet the specific needs of these communities.

Canada has the largest biomass per capita in the world [58], with 9 % of the world's forests. However, bioenergy accounts for only about 5 % of Canada's total energy supply [59]. To meet the United Nations General Assembly's initiative, replacing diesel with wood-based bioenergy in remote and Indigenous communities is part of Canada's strategy [60,61]. Several studies have shown that replacing fossil fuels with local bioenergy sources (within 100 to 300 km) can reduce greenhouse gas (GHG) emissions in Canada, with carbon parity times ranging from immediate to over a century [62–65]. For example, Thompson and Duggirala [66] estimated that switching from diesel-generated energy to a biomass system in an off-grid community in Ontario could save up to 497 tons of CO_2 per year. Buss et al. [67] explored the GHG mitigation potential of using wood-based bioenergy in northern and isolated communities, using Fort McPherson, an Indigenous community in the Northwest Territories, as a case study. They estimated an installation cost of CAD 1,800/kW installed and a production cost of CAD 0.121/kWh. The results showed that replacing diesel with bioenergy could reduce GHG emissions by up to 32,166 tons of CO_2 equivalent over 100 years, with achievable benefits ranging from 0 to 20 years for local wood chips and 2 to 37 years for imported pellets. These studies emphasize that the benefits (economic and ecological) are sensitive to transport distance and the efficiency of biomass boilers. To maximize benefits, supply chains should be local.

Research shows that hydropower plays an important role in the energy mix of the Arctic. Fig. 5 illustrates the distribution of installed renewable technology capacity in Arctic communities (a) and the percentage of energy produced by these technologies (b). This includes isolated communities in Alaska, Canada, Greenland, and Norway. It is observed that although hydropower accounts for less than 25 % of the installed capacity, it generates more than 40 % of the total electricity production in Arctic communities. Several projects demonstrate the potential of hydropower. One significant example is the Innavik power plant, a run-of-river hydropower plant with a capacity of 7.5 MW, which provides renewable electricity to the community of Inukjuak in Nunavik. This installation helps reduce the community's dependence on diesel for electricity, heating, and hot water by 80 % [68].

One advantage of hydropower is that it is a controllable energy source and is generally easy to manage regarding production performance. This allows for adjusting the amount of energy generated according to demand, providing flexibility in integration with other renewable energy sources, particularly intermittent ones like wind or solar. Additionally, it is a technology that supports local job creation [70]. However, in the case of run-of-river hydropower plants, these installations alter the natural flow of rivers and can impact fish migration and the local environment [71]. Indeed, in most cases, a dam can become an insurmountable barrier for fish, which could lead to a reduction in fish populations upstream of the dams in hydropower plants.

The literature highlights that energy production cannot rely on a single renewable source. Although resources like solar, wind, and hydropower offer significant potential, each has inherent limitations that can compromise their long-term reliability. For example, the intermittency of wind and solar sources creates variability in production, making it difficult to continuously meet energy demands without resorting to storage solutions or backup energy sources. Thus, an integrated approach, combining multiple renewable energy sources suited to local specificities, appears to be the most effective way to ensure stable, reliable, and sustainable energy production. In this context, Sani et al. [72] determined the optimal configuration of 100 % renewable systems for isolated communities using an economic, ecological, and societal optimization model. Four representative communities were selected: Kasabonika, Cap-aux-Meules, Carcross, and Barren Lands, spread across Canada. The results show that the optimal renewable energy mix varies based on the specific characteristics of each community, such as climate, resource availability, and geographical location. Communities with high wind speeds, low solar radiation, very low temperatures, and limited biomass availability depend heavily on wind, accounting for 80.7 % of their energy production. Communities with moderate wind and solar resources, along with some biomass, also rely significantly on wind, providing 89.5 % of their energy. Coastal communities with strong winds, lower solar radiation, milder temperatures, and biomass reach the highest wind energy production at 92.9 %. In contrast, communities with low winds but high solar radiation would primarily use photovoltaic panels to supply 49.6 % of their energy demand.

Combining multiple sources would help compensate for the fluctuations of each source and optimize energy yields while reducing dependence on fossil fuels and minimizing environmental impacts. For this reason, in many scenarios, experts recommend developing hybrid systems that integrate different renewable technologies while utilizing energy storage solutions to maximize the autonomy of local energy systems.

2. Energy storage for Canadian off-grid communities

Reducing dependence on carbon-based energy in off-grid communities requires the integration of renewable energy sources, accompanied by appropriate storage solutions to compensate for their intermittency. This section examines the main energy storage technologies studied in these communities. Overall, there are three types of energy storage: thermal, mechanical, and chemical [73]. Each of these solutions has specific advantages in terms of storage capacity, cost, and adaptability, but they also face challenges, particularly related to extreme climatic conditions and the necessary infrastructure. This

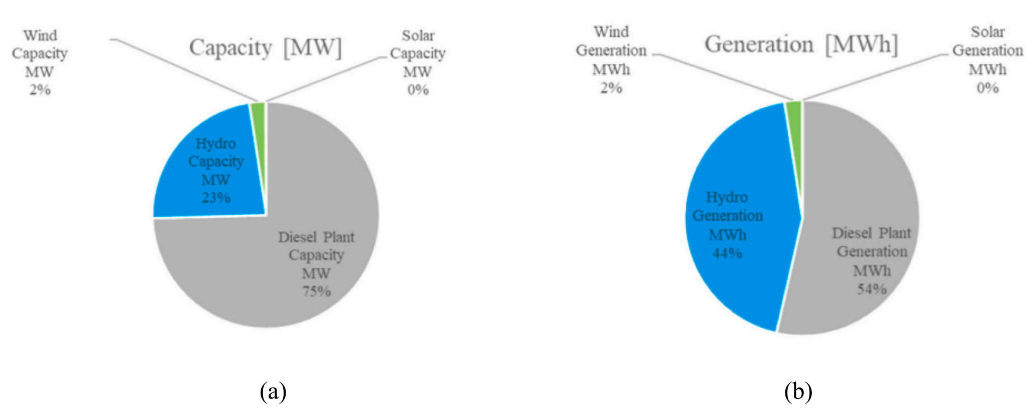


Fig. 5. (a) Percentage distribution of installed capacity of renewable technologies in Arctic communities and (b) percentage of energy produced by these technologies [69].

section aims to present the current state of research and applications of these technologies for off-grid communities in Canada.

2.1. Thermal energy storage

Thermal energy storage is a technology that allows energy to be stored in the form of heat or cold by heating or cooling a storage medium. Depending on the storage temperature, this energy can be mobilized for various applications, such as heating, cooling, or even electricity generation.

Thermal energy storage is a common solution for storing excess energy in the form of heat, typically in external tanks that contain a fluid or material capable of storing this energy [74]. However, no specific studies have been conducted on this "classic" solution in the context of off-grid communities in Canada, mainly due to the extreme climatic conditions. Indeed, the extremely low temperatures in these regions present a major challenge for thermal storage. The main issue lies in significant thermal losses, as storage tanks exposed to freezing temperatures quickly lose heat, compromising the system's efficiency [75]. To counter this phenomenon, solutions such as thermal insulation of the tank or the construction of protective structures like sheds or dedicated buildings would be necessary to maintain the heat. However, these measures increase installation costs, which could make this technology economically less viable for these isolated communities. In addition to the additional costs, the efficiency of thermal storage solutions in these cold environments would also be limited by logistical constraints, such as the difficulty of transporting and maintaining equipment in remote areas.

2.1.1. Borehole thermal energy storage

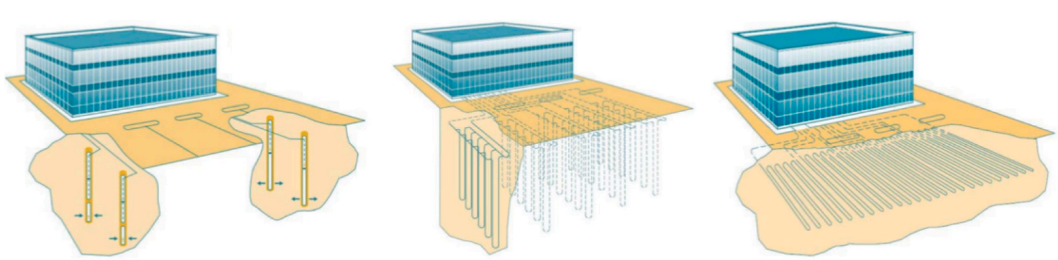
The most studied form of thermal energy storage in northern regions is borehole thermal energy storage (BTES). The most common geothermal heat exchangers are open loops using groundwater directly (a), as well as closed vertical (b) and horizontal (c) loops where a mixture of antifreeze circulates [76] (see Fig. 6).

However, an open-loop heat exchanger is not recommended for subarctic regions, as the ground temperature remains close to 0 °C year-round, which could lead to freezing of the water and thus cause significant technical issues in the system. On the other hand, horizontal closed-loop exchangers [78,79] and vertical well heat exchanger systems [80–82] can provide heating for a building in a subarctic climate using an antifreeze, such as propylene glycol, which can be mixed with water and used as a heat transfer fluid. The principle of BTES is based on using boreholes in the ground to install heat exchangers that capture heat from the ground and store or transfer heat to a heat transfer fluid for later use [83]. One of the main advantages of BTES is its ability to store large quantities of heat stably and reliably, regardless of external climate variations. Additionally, BTES can operate continuously without significant heat loss, unlike conventional thermal storage tanks, making them particularly suitable for cold regions.

Giordano and Raymond [82] explored the use of BTES in a subarctic climate to address the technical challenges posed by low temperatures. A system combining 1000 m^2 of solar collectors and 100 heat exchangers, each 30 m deep, was simulated in Kuujjuaq, Nunavik, to partially cover the heating needs of a potable water pumping station. Fig. 7 highlights the advantage of BTES in this context: the undisturbed ground temperature, which remains stable around 0 °C, contrasts with the external temperatures that can drop as low as −25 °C. The results show that after three years, the system can achieve a solar fraction of 45–50 %, a heat recovery of over 60 %, and save 7000 L of diesel annually. A 50-year cost analysis reveals that, with proper incentives, the levelized cost of energy can be comparable to or lower than the current diesel-dependent situation, especially if electricity is sourced from renewables. It was estimated between CAD 0.28/kWh and CAD 0.49/kWh produced.

Kuujjuaq, the capital and largest village in Nunavik, is not connected to the Quebec electrical grid and thus relies entirely on fossil fuels for electricity and heating production [84]. Each home is equipped with a diesel boiler and an oil tank to meet daily heating needs. While diesel boilers can meet local heating demand, it is important to note that the diesel combustion process generates significant pollution, which has negative environmental impacts. Solar resources have demonstrated their potential in the subarctic region [85]. However, these solar resources are abundant only in summer, while the peak heating demand occurs in winter. Therefore, searching for an efficient seasonal thermal energy storage system has become imperative to harness this intermittent heat source [86].

Several studies have demonstrated that BTES is a promising technology for harnessing solar energy throughout the heating season and bridging the seasonal gap between supply and demand [87]. Unlike batteries and other short-term storage solutions, this principle can store thermal energy from solar fields for months or even years and deliver it on demand to users, regardless of ambient temperatures or solar availability [88]. Wu et al. [89] evaluated the potential of a collective solar heating system with underground thermal storage to reduce diesel dependence in the subarctic region of Nunavik. A system comprising 1500 m^2 of solar collectors and 150 buried heat exchangers, each 30 m deep, was analyzed through a life cycle assessment to compare its environmental performance with that of domestic diesel boilers. The results showed that the system is efficient regarding human health, climate change, and resource management, with a reduction of CO_2 emissions by 22.4 % and a 21 % improvement in overall environmental impact. However, its impact on ecosystem quality is slightly higher due to land occupation and the drilling required. Comeau et al. [90] conducted a preliminary evaluation of geothermal resources in northern Quebec and created a map of the distribution of average thermal conductivity. Soils with low thermal conductivity are favorable for thermal energy storage systems, while high thermal conductivity may be suitable for geothermal heat pump systems. Miranda et al. [91] studied the feasibility of shallow geothermal applications in Nunavik, such as BTES, and confirmed that they would be feasible in areas where rock conductivity is moderate to low to prevent heat losses from the underground



(a) (b) (c)

Fig. 6. (a) Open-loop system, (b) Vertical loop, and (c) Horizontal loop [77].

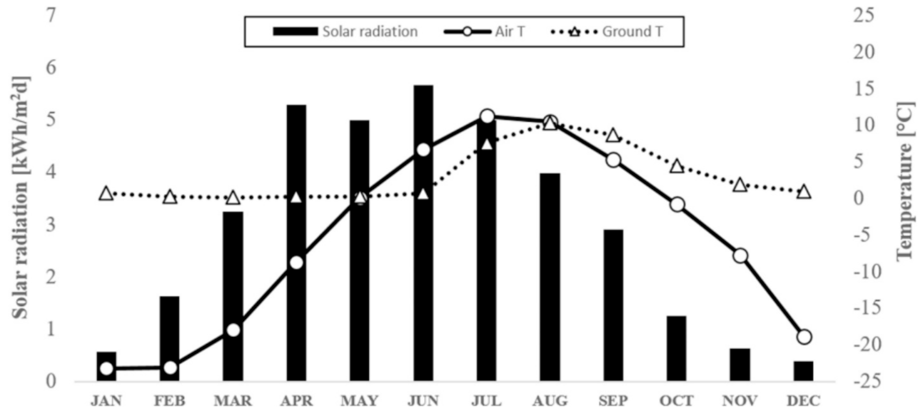


Fig. 7. Monthly solar radiation, mean air temperature and mean ground temperature (at 0.25 m below surface) at Kuujjuaq [82].

storage volume. Labgevin et al. [92] assessed the efficiency, heating costs, and relevance of geothermal systems assisted by solar energy in a subarctic climate. Detailed subsurface data collected in Whapmagoostui–Kuujjuarapik were used to simulate heat pumps coupled with vertical heat exchangers, considering the possibility of thermal energy storage. The results show that a conventional vertical heat exchanger configuration efficiently meets low heating needs, while thermal energy storage in the ground allows for annual load balancing and meets higher heating demands.

This storage principle directly utilizes the ground and rock to store thermal energy [93–95]. Heat injection leads to temperature variations in the surrounding soil formations, affecting the boreholes' stability and the system's operational lifespan [96–98]. Therefore, it is crucial to have a precise and comprehensive understanding of the risks associated with this behavior. Sojoudi et al. [99] evaluated the impact of thermal disturbance generated by seasonal underground thermal storage in the town of Kuujjuaq. A numerical analysis examined the soil's response during system operations. Based on the modeling results, a maximum storage temperature of 60 °C tends to cause considerable vertical displacement. In contrast, the vertical displacement for the case with a maximum temperature of 30 °C is much less significant. This temperature must be carefully considered in a long-term analysis, as it could lead to soil subsidence: it is essential to avoid degrading the frozen soil, which ensures the stability of building foundations.

2.1.2. Rock piles thermal energy storage

Permafrost is a major obstacle to BTES systems. To overcome this challenge, a promising alternative is rock piles thermal energy storage (RPTES). This system relies on using large quantities of stones or gravel as thermal storage materials. Heat is transferred through a fluid, such as air or water, which flows through the rock pile to either store or extract thermal energy.

A diesel generator combines an internal combustion engine (typically a diesel engine) and an electric generator. Even with the best available technologies, the diesel engine only achieves an efficiency of about 35 %. Typically, up to 65 % of the total energy consumed is lost as heat [100]. Therefore, it can be estimated that for every 3 kW of energy from the consumed fuel, only 1 kW is converted into electricity, while the remaining 2 kW is lost, half of which (1 kW) ends up in the exhaust gases [101,102]. Recovering the residual heat from the exhaust gases of a diesel generator can be an indirect way to save a significant amount of fuel and reduce the system's impact on global warming [103]. Although several studies explore the potential of waste heat recovery systems, the focus is generally on using the heat for electricity generation through organic Rankine cycles [104–108] or thermoelectric generators [109,110], mainly due to the flexibility of electrical energy. However, several studies have suggested reusing and storing this heat. Amiri et al. [111] and Ghoreishi-Madiseh et al. [112] studied the use of seasonal RPTES to exploit the residual heat from the exhaust gases of diesel generators in remote Arctic communities and use it for building heating during the winter. The application case is the Kwadacha community in British Columbia. Fig. 8 illustrates the principle of this system.

In summer, the excess heat from generators is often wasted due to a lack of demand. The goal is to store this heat in the rock pile during the summer and release it in winter. The proposed system uses large untreated or crushed rocks, which can come from waste produced by nearby industrial (mining) activities. A concrete dome is planned as a protective measure against weather conditions. The sidewalls of the pile feature a layer of thermal insulation material to prevent heat loss. The study proposes a validated numerical model to assess the performance of this storage system. The construction cost was estimated at approximately CAD 0.74/kWh. A techno-economic evaluation shows a payback period of less than six years, making this solution sustainable and economically viable.

In a different context, Ghoreishi-Madiseh et al. [113] studied the application of the RPTES to optimize ventilation management in a mine. The principle relies on seasonal storage: the heat extracted from the air in summer is stored in the rock to be reused in winter, while the cold winter air is captured to cool the air in summer. The authors developed a three-dimensional transient model simulating thermal exchanges between the ventilation air and the storage to assess the system's performance. The results of this modeling show a significant reduction in energy consumption, with the system capable of adjusting the ventilation air temperature by 15 to 20 °C depending on seasonal needs. This study highlights the potential of large-scale seasonal thermal storage to improve the energy efficiency of mining operations while reducing reliance on fossil fuels and lowering carbon footprints. Similarly, Rodrigues de Brito et al. [114] proposed recovering residual heat from diesel generator exhaust gases using a system with heat exchangers to preheat the intake air for underground mines. Their results show that the system could meet 75 % of heating needs, generating annual savings of CAD 6.7 million and achieving a payback period of less than one year. The paper also recommends integrating seasonal RPTES to maximize efficiency, particularly in summer, and further reduce reliance on fossil fuels.

In addition to energy, nutrition is one of the main challenges faced by Indigenous communities. Global changes have made it increasingly difficult to access traditional foods such as wild fish, animals, and berries, while imported products, delivered by ship or plane, are becoming more expensive. Over the past 20 years, several community greenhouse initiatives have been launched in various villages across Nunavik. In 2016, the community greenhouse in Kuujjuaq was instrumented, revealing significant day/night temperature differences that hinder optimal plant growth [115]. To mitigate daily temperature variations, a rock bed was installed directly beneath the plant soil in the fall of 2018 to serve as a short-term heat storage medium. An air circulation

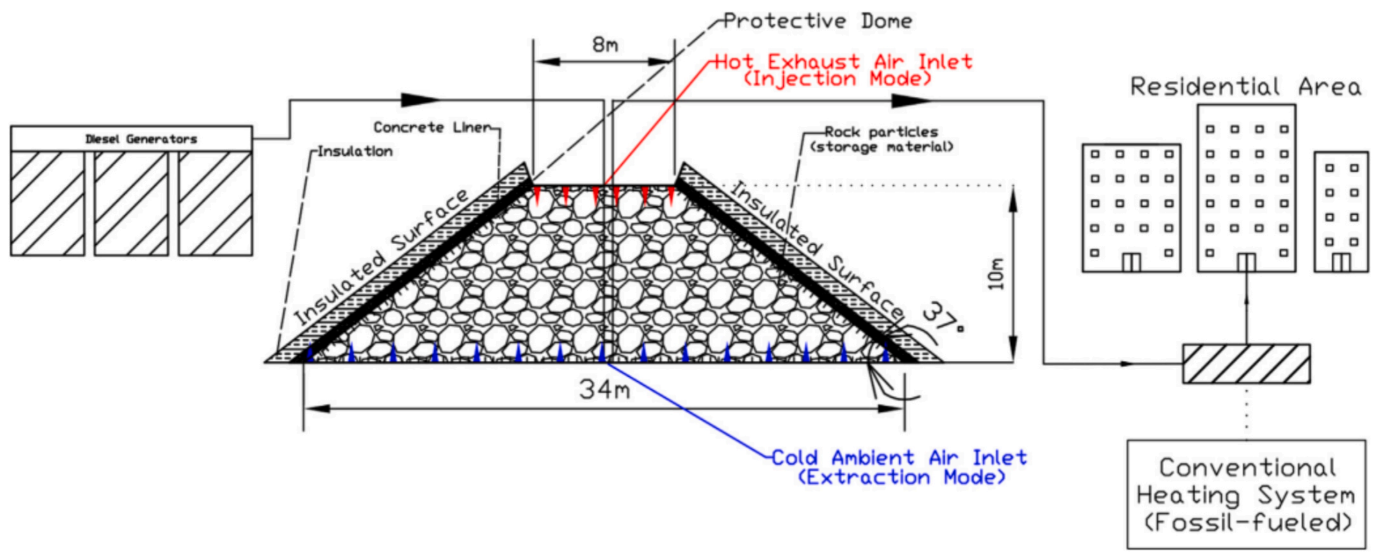


Fig. 8. Rock piles thermal energy storage (RPTES) system diagram [111].

system was implemented to transfer heat to the rocks during the day and release it back at night [116,117]. Local rocks were used as the storage medium, with air as the heat transfer fluid. Results showed that the system is reliable and can recover 40 to 50 kWh of thermal energy that would otherwise be lost through air ventilation. More broadly, studies demonstrate that storage technologies can be a promising and cost-effective option for providing renewable heat to northern greenhouses, allowing for earlier planting and extending the growing season by at least 2 to 3 weeks [117].

2.2. Mechanical energy storage

In mechanical energy storage systems, energy is stored by converting it between mechanical and electrical forms [118]. The main advantage of this type of storage is its ability to quickly convert and release stored mechanical energy [119]. Studies focusing on northern Canadian communities highlight three main mechanical storage technologies: pumped hydro, compressed air, and flywheel energy storage.

2.2.1. Pumped hydroenergy storage

Pumped hydroenergy storage (PHES) is a hydroelectric storage method that preserves electrical energy as gravitational potential energy. Water is pumped to an upper reservoir during periods of low electricity demand and then released to flow through turbines to generate electricity during peak demand periods. The amount of energy stored depends on the height difference between the upper and lower reservoirs and the volume of water [120]. This technology is well-known for its large energy storage capacity, long lifespan, and favorable storage efficiency [121].

In Canada, PHES represents the primary form of energy storage, despite the existence of only one operational facility: the Sir Adam Beck Pump Generating Station in Ontario (174 MW) [122]. In Ontario, the government has initiated preliminary work on a 1 GW/11 GWh PHES project in Meaford, with an investment of up to CAD 285 million [123]. This project is part of a broader energy strategy aimed at meeting an anticipated 75 % increase in electricity demand by 2050. The Canyon Creek pumped hydro energy storage project, led by TC Energy, represents a potentially significant contribution to Alberta's energy transition [124]. With a generation capacity of up to 75 MW, it will be capable of delivering up to 37 h of dispatchable energy as well as on-demand ancillary services to support the stability of the provincial power grid. Rahimzadeh et al. [125] analyzed various storage systems for residential buildings in British Columbia. Their study highlights that for 100 % renewable off-grid systems, Li-ion batteries and PHES effectively manage daily and seasonal intermittencies. In a study on transitioning communities to clean energy systems, Bayera Madessa et al. [126] emphasize the potential role of PHES in achieving this goal. Koritarov et al. [127] identified Alaska's significant potential for developing PHES projects, both on a large scale for the grid and for isolated communities. Over 1,800 sites were identified, with a total storage capacity of approximately 4 TWh. Small-scale projects, suitable for remote communities, account for nearly 50 % of the potential sites, primarily located in southeastern Alaska.

The main constraint of PHES lies in the availability of a suitable geographical site. This type of storage requires natural topography, such as mountains or valleys, to create water reservoirs at different altitudes or costly artificial infrastructure to achieve the same effect. In northern regions, extreme climatic conditions, including long and harsh winters, can complicate the construction of such facilities and impact their long-term performance due to issues like freezing. Repurposing abandoned mining networks could be a viable solution to address this challenge in a mining context. At the Raglan mine, the design and sizing of a wind farm coupled with underground pumped hydro energy storage were undertaken to reduce diesel dependency and greenhouse gas emissions [128]. The most promising simulation estimates a payback period of 11 years, with an annual reduction in greenhouse gas emissions of 68,500 tCO_2eq and an 88.6 % decrease in diesel consumption. Investment costs are estimated at CAD 2,080/kW for wind turbines and CAD 3,720/kW for storage. Operating and maintenance costs are projected at CAD 17.3/MWh and CAD 72.5/kW-year, respectively. The study concludes that such storage systems are theoretically feasible, but it emphasizes the need for further research to assess the proposed sites' viability and conduct more in-depth economic analyses.

According to a report published by WaterPower Canada, the country has vast potential for pumped storage hydropower (PSH), with over 8,000 GW of realistic capacity identified across nearly 1,200 sites—-primarily in British Columbia, Quebec, and Newfoundland and Labrador [129]. A study conducted by the Australian National University identified 616,000 potential PHES sites worldwide through an analysis based on geographic information systems [130]. For Canada, this study revealed an impressive storage potential exceeding 2.107 GWh. This research is of great significance not only because of the vast amount of data generated but also because the researchers developed an interactive map that allows for the visualization of all potential sites along with detailed information for each region worldwide. Among these details are parameters such as altitude, reservoir volume, distance between reservoirs, as well as the power and potential energy stored [131]. For example, Fig. 9 presents data related to a potential site near the Kuujjuaq community in Northern Quebec.

This particular site has a water height of 100 m, with a distance of 0.6 km between the two reservoirs. The water volume is estimated at 699 gigalitres (GL), with a recoverable energy capacity of 150 GWh and a storage duration of 50 h. These parameters provide an overview of each site's energy storage potential and project feasibility. However, it is important to note that although innovative and promising, this map has some significant shortcomings. None of the sites mentioned in the study have undergone geological, hydrological, environmental, or other specific feasibility assessments. Furthermore, the accuracy of the potential sites directly depends on the precision of the source data used to generate these maps. As a result, some potential sites may be located in protected areas, urban zones, or other sensitive areas not properly identified by the data sources. Despite these limitations, this tool represents a significant advancement in studying PHES potential and paves the way for further research and analyses.

Despite numerous potential sites, the technical and material challenges associated with PHES are significantly more demanding than those of other storage technologies. Constructing this type of storage in remote regions requires substantial logistical investments and specialized materials, which can pose an added challenge in isolated areas with limited access to resources and skilled labor. Furthermore, maintaining turbines in these extreme conditions can be both complex and costly. While PHES remains a promising technology, its implementation in northern Canadian communities necessitates meticulous planning and a detailed assessment of the technical, logistical, and economic constraints.

2.2.2. Compressed air energy storage

Compressed air energy storage (CAES) stores energy by compressing air [132,133]. CAES has been proposed as an alternative to PHES, which relies on specific geological conditions and raises various environmental concerns. This technology has demonstrated economic feasibility, high reliability, and minimal environmental impact [132].

Using Kangirsuk, an Inuit village in northern Canada as a case study, Sarmast et al. [134] proposed a sizing strategy for a small-scale CAES system integrated with a wind-diesel power plant. The study demonstrated that integrating this system could significantly reduce diesel fuel consumption, achieving a 55 % reduction with a single wind turbine and a CAES system and 63.4 % with two wind turbines. These results suggest that CAES holds significant potential to reduce diesel dependency and promote energy sustainability in remote regions. However, while the findings are promising, they also highlight the need for a comprehensive feasibility assessment of CAES in such communities, considering technical, economic, and environmental factors. For instance, the first scenario, involving a single wind turbine, showed an initial cost of $5,080,000, a substantial investment for an isolated community. Meanwhile, the second scenario, which includes two wind turbines, offers a greater reduction in diesel consumption (63.4 %) but requires an even higher initial investment of $9,980,000. Although the second scenario entails higher short-term costs, it could be the preferred choice for ensuring long-term energy sustainability, provided that capital costs are effectively managed.

Adib et al. [135] presented a design approach for an energy system combining wind turbines, a CAES system, and diesel generators for Kuujjuaq. The study provided a detailed mechanical design and configuration of the storage system. The findings indicate that this system offers a promising, cost-effective, and reliable energy solution for isolated regions, achieving significant reductions in average daily costs and CO_2 emissions by 69 % and 76 %, respectively. Ibrahim et al. [136] conducted a case study on two different scales of hybrid wind-diesel CAES systems: small-scale and medium-scale. The small-scale CAES system was modeled for a telecommunications station in Kuujjuarapik, with an average load of 5 kW. The medium-scale system was modeled for the Tuktoyaktuk community in the Northwest Territories, with an average load of 544 kW. Results showed a 97.7 % reduction in diesel fuel consumption for the small-scale application and a 27 % reduction for the medium-scale system.

Other studies in the same community highlighted that CAES is the most efficient, least polluting, cost-effective, and high-performing solution compared to batteries and hydrogen storage [137,138]. Although modern batteries are more efficient, they remain expensive and require

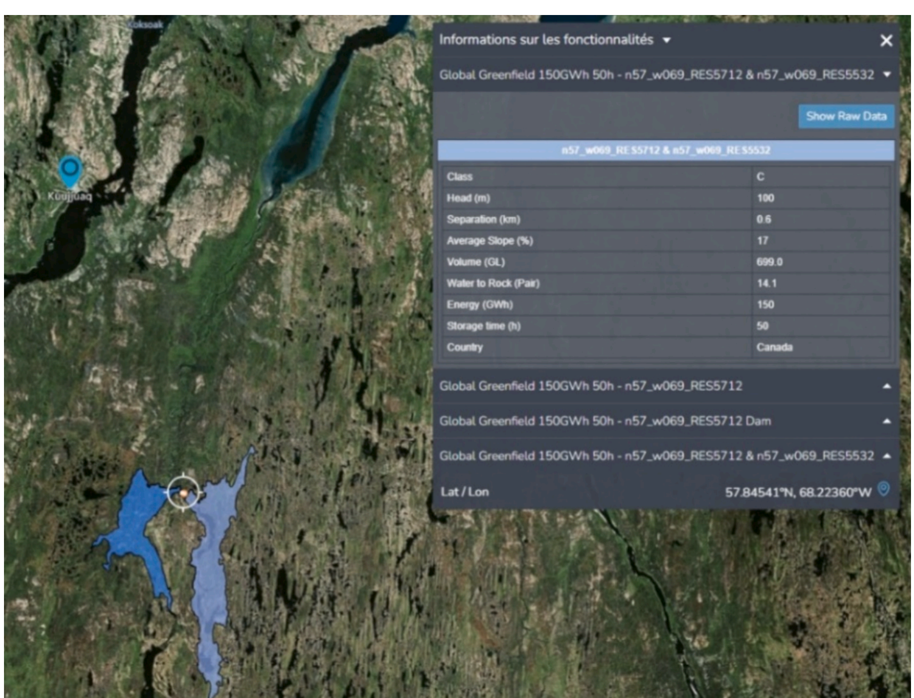


Fig. 9. Data on a potential site for integrating a PHES near the community of Kuujjuaq [131].

converters (AC-DC), control systems, and regular maintenance. Additionally, end-of-life recycling challenges need addressing. On the other hand, hydrogen storage combined with fuel cells for electricity production is hindered by the prohibitive cost of electrolyzers and low overall efficiency (around 35 %).

In addition to the classic CAES configuration, several variants have been explored to optimize the system. Basbous et al. [139] evaluated the potential fuel savings of a hybrid wind-diesel CAES system in Tuktoyaktuk. In their study, the researchers introduced a hybrid pneumatic combustion engine, called a bi-source engine, representing a variant of a conventional diesel engine. This engine has the unique ability to operate both as an air compressor in addition to its standard function as a diesel engine. The study's results showed that implementing a wind-diesel autonomous system with a wind energy penetration rate of one led to a 53.5 % reduction in the community's fuel consumption. The analysis also revealed that both the air storage capacity and the wind energy penetration rate significantly influenced fuel savings. An evaluation of a regenerative air energy storage (RAES) system within a wind-diesel microgrid was conducted by Manchester et al. [140]. The RAES is a CAES system that improves storage efficiency by utilizing waste heat from diesel engines to preheat the compressed air before it enters an air expander. This study assessed the impact of wind energy penetration rates and RAES storage capacities on diesel fuel savings for a remote community in Canada. The modeling results indicated that a 36 % fuel savings could be achieved with an optimal system configuration involving a 1 MWh RAES with a wind energy penetration rate of 75 %. The installation cost of wind turbines was estimated at CAD 4,500/kW, while that of the RAES was estimated at CAD 2,000/kW. This configuration leads to a payback period of 6 years.

2.2.3. Flywheel energy storage

The flywheel energy storage (FES) system is a mechanical technology that harnesses kinetic energy, specifically the rotational energy of a heavy cylinder, to store electricity [73,141]. Flywheels have recently garnered increased attention as a mechanical storage technology. They offer higher power capacity and a lower cost per power unit than batteries. Flywheel energy storage systems are more environmentally friendly because they do not contain chemical components. Additionally, they offer a fast response time and a long lifespan, even after numerous use cycles [141].

In scientific literature, few studies specifically address the installation of flywheels in isolated communities. However, several studies mention flywheels as a storage solution at the Raglan mine [128,142,143]. This system includes a 200 kW, 1.5 kWh flywheel for rapid transients. Hitachi Energy has installed two flywheels, each with a capacity of 1 MW, on Kodiak Island, Alaska [144]. This island, home to approximately 15,000 people, aims to operate entirely on renewable energy. The flywheels are combined with a battery system, providing a promising solution for the future. Flywheels can protect batteries from frequent charge and discharge cycles, therefore extending their lifespan. By integrating a flywheel with batteries, the aging process of the batteries can be significantly slowed, with an estimated improvement of 300 % [145].

The main challenge remains the rapid loss of capacity over time, but a long-lasting flywheel could address this issue. However, a techno-economic comparison between long-duration flywheels, lithium-ion batteries, and lead-acid batteries for applications in isolated microgrids has shown that long-duration flywheels are unlikely to capture a significant market share. This is due to their levelized cost of energy (LCOE) and the rapid decline in lithium battery prices [146].

2.3. Chemical energy storage

Among the three energy storage alternatives, the last one involves converting energy into chemical form [147]. Two main chemical storage technologies are being studied in the context of northern Canadian communities: electrochemical batteries and hydrogen-based systems. These include producing and storing hydrogen to be used in fuel cells for electricity generation.

2.3.1. Energy storage using electrochemical batteries

An electrochemical energy storage system, also known as battery storage, is a technology capable of converting chemical energy from electrochemical reactions into electricity [148]. According to forecasts from S&P Global Commodity Insights, global battery production capacity is expected to experience dramatic growth in the coming years. For instance, lithium-ion battery production capacity is projected to increase from 2.8 terawatt-hours (TWh) at the end of 2023 to approximately 6.5 TWh by 2030 [149]. Several studies have explored this type of storage in the context of off-grid communities in northern Canada.

Two batteries are currently operational in villages in Nunavik: a 600 kW / 600 kWh battery in Quaqtaq and a 900 kW / 900 kWh battery in Kuujjuarapik [150]. Echoing the frequent focus on BTES mentioned in section 2.1.1, Maranghi et al. [151] developed a detailed model of a geothermal heat pump assisted by solar photovoltaic energy designed to heat a house in the community of Whapmagoostui-Kuujjuarapik. Simulations were conducted both with and without electrical storage. The electrical storage consisted of batteries whose type was not specified. Strong assumptions were made for the modeling: 100 % charge and discharge efficiency and 100 % depth of discharge. Over 10 years, the system significantly reduced fuel consumption, with respective decreases of 38.2 % (without batteries) and 59.1 % (with batteries).

These assumptions, however, can be criticized. Extreme weather conditions, particularly subzero temperatures, can degrade the performance and reliability of batteries. Low temperatures reduce battery capacity, output power, and charging efficiency [152]. In this context, Ahoutou et al. [153] conducted a comparative review of various electrochemical storage technologies, focusing on their performance under the harsh climatic conditions of Northern Canada. The authors highlight the advantages of lithium-ion batteries over other technologies (lead-acid, Ni-Cd, Ni-MH, Li-Po, etc.), such as longevity, high working voltage, low self-discharge rate, higher energy density, and compactness. However, they also note that despite efforts to improve low-temperature performance through advancements in battery materials, this remains a significant challenge, and no definitive solution has yet been found. Substantial research is still needed to quantify degradation mechanisms, reliability criteria, and safety risks, specifically for cold climates. Predictive models, in particular, need to be refined using empirical data from real-world systems [154].

Scientific literature highlights that this type of storage is less suitable for large-capacity applications. For instance, in the case of mining operations, the cost of electricity storage is the primary factor limiting the complete decarbonization of energy systems [155,156]. Despite reducing battery costs over the past decade, they remain relatively expensive and have a short lifespan [157]. As a result, in many cases, the costs associated with battery storage make the implementation of renewable systems economically uncompetitive compared to conventional diesel-based counterparts. This renders them prohibitive for large-scale mining applications. At the Raglan mine, the design and sizing of a vanadium redox flow battery system coupled with a wind farm have been proposed [143]. The most significant diesel savings are achieved with a system comprising 12 additional wind turbines, a 20 MW/160 MWh redox battery, and no continuously operating generators. This configuration allows for diesel savings of up to 64 %, corresponding to a reduction of approximately 68,000 tCO_2eq emissions. However, the study concludes that the current cost of the technology is too high to consider the actual installation of a system with several tens of megawatt-hours, with costs exceeding $150 million for 120 MWh. Additionally, the harsh climate necessitates the construction of a shelter to maintain the batteries at an appropriate temperature. This construction also involves significant costs and requires considerable land use.

Vera et al. [158] developed an optimization model for the long-term planning of microgrids in remote Canadian communities, integrating renewable energy sources and energy storage systems, including lithium-ion batteries. The case study focused on Sanikiluaq, a village located on the northern shore of Flaherty Island in the Belcher Islands, Hudson Bay, Nunavik. Their results indicate that wind resources, along with solar and storage technologies, can play a crucial role in meeting the electricity demand of remote communities while significantly reducing operating costs and greenhouse gas emissions, with reductions of approximately 51.9 % in this study. In addition to lithium-ion batteries, the optimization model also incorporates hydrogen production and storage components, such as electrolyzers, storage tanks, and fuel cells. Kalantari et al. [159,160] explored renewable energy solutions to replace diesel in remote mines in cold climates, addressing environmental concerns related to greenhouse gas emissions. They emphasize that, although progress has been made toward adopting green energy, the high cost of battery storage systems remains a barrier to the complete decarbonization of mining energy systems. Hydrogen and thermal storage systems are presented as more cost-effective alternatives. The study highlights that hybridizing fuel cells and batteries for electrical storage provides superior economic performance compared to standalone solutions.

2.3.2. Hydrogen production, storage, and use

Hydrogen is widely regarded as a sustainable and clean energy storage medium [161,162]. A hydrogen energy system primarily consists of three subsystems: (i) an electrolyzer to convert water into hydrogen, (ii) a storage tank for the hydrogen, and (iii) a fuel cell as a conversion unit to transform the stored hydrogen back into electrical energy. During the charging phase, surplus energy is used in the electrolysis process to split water into oxygen and hydrogen, with the latter being stored in dedicated tanks. During the discharging phase, fuel cells are used to convert the stored hydrogen back into electricity [163]. Several studies have focused on the role of hydrogen as a storage solution for off-grid communities in northern Canada.

Rezaei et al. [164] presented an environmental and economic optimization of a system based on biomass gasification (wood pellets), combining heating, hydrogen production, and electricity generation. The study demonstrates that integrating hydrogen production with combined heat and power generation is economically advantageous. The total cost of the entire system is estimated to range between CAD 0.295/kWh and CAD 0.298/kWh. Sani et al. [72] developed an optimization model designed to balance economic, environmental, and social objectives to determine the optimal configuration of 100 % renewable systems for remote communities. This model evaluated hydrogen as an energy storage solution to address seasonal fluctuations. The results indicate that hydrogen could be an excellent long-term energy storage option to mitigate energy shortages during winter.

Puranen et al. [165] examined the technical feasibility of an off-grid energy system combining short-term storage (batteries) and seasonal hydrogen storage. Although not specific to Canadian communities, the study focused on a single-family residence in Finland equipped with a 21 kW photovoltaic system and a geothermal heat pump for heating. The study concluded that technically feasible solutions exist for the proposed system, with the most critical factor being the high peak power demand during periods of low photovoltaic generation. The battery storage requirement was modest, at approximately 20 kWh. However, the system required fuel cell and electrolyzer capacities of at least 4 kW and 5–7 kW, respectively, for effective off-grid operation. The hydrogen storage demand, estimated at 170–190 kg annually, was deemed excessive for this residential context. Meriläinen et al. [166] explored converting a Nordic townhouse in Finland, previously heated with oil, into a carbon–neutral building by combining energy efficiency improvements with an autonomous system powered by photovoltaics, wind, and energy storage systems (batteries and hydrogen). The system utilized photovoltaics and wind energy as primary sources to supply electrical loads and recharge battery energy storage systems (BESS) and hydrogen storage systems. Fig. 10 illustrates the system's operating principle.

The primary energy sources are a photovoltaic solar system and a wind turbine, which supply electricity directly to electrical loads and recharge energy storage systems, including BESS and hydrogen storage. In winter, when solar power generation is limited due to low solar irradiation and wind energy cannot fully meet energy demands, the fuel cell acts as a secondary energy source. However, fuel cells are not well-suited for dynamic load-following and are primarily used to recharge the BESS, providing a stable energy reserve to handle fluctuating power demands [167]. The fuel cell operates using hydrogen produced by an electrolyzer, powered by surplus energy from the primary sources. A key feature of the system is the recovery of residual heat from the fuel cell and electrolyzer. This heat is utilized for space heating and domestic hot water, reducing dependence on other heat sources. This strategy optimizes resource utilization, particularly when heating relies on a heat pump. Despite its technical feasibility, the concept faces high costs. The levelized cost of energy (LCOE) is estimated at approximately CAD 1.10/kWh, which represents the least expensive configuration. However, this cost is significantly higher than that of grid-connected electricity in Finland. Nevertheless, in remote communities in Canada, where energy costs are considerably higher, this system could become economically viable.

In the case of higher demand, the design and sizing of a hydrogen storage system coupled with a wind farm was proposed for the Raglan mine [142]. The analysis concluded that decarbonizing the mine is technically possible, but the economic aspect is problematic. Over 15 years, none of the scenarios studied were profitable. This is due to the still high costs of hydrogen technologies and the need for large storage tanks. Solid fuel cells could be an option to optimize costs since they can produce both electricity and heat. However, this technology is still in its early stages on the market. Temiz and Dincer [168] designed and studied an innovative system to produce energy, food, fuel, and water for Arctic communities. The study focused on the town of Kugaaruk, located in Nunavut. The system combines ocean thermal energy conversion with an ammonia-based Rankine cycle, a concentrated solar power plant, bifacial photovoltaic panels, a cascade heat pump, multi-effect desalination systems, PEM electrolyzers for hydrogen production, fuel cells, and both hydrogen and thermal energy storage systems. According to the authors, the system demonstrates energy viability, achieving energy and exergy efficiencies of 16.3 % and 36.4 %, respectively. However, the study does not include an economic analysis, and the costs of implementing all these systems would likely make the project financially unfeasible.

2.4. Summary and outlook

This section has presented the current state of research and applications of storage technologies for remote communities in northern Canada. These technologies, which are essential to meet the energy needs of these isolated regions, provide diverse solutions based on the availability of local resources, climatic constraints, and economic requirements.

BTES is a key solution for northern regions due to its ability to sustainably store large amounts of heat. Unlike open-loop systems unsuitable for subarctic climates, closed-loop systems with antifreeze fluids provide reliable and stable performance. Several studies have demonstrated significant reductions in diesel use and CO_2 emissions, although drilling and land use have notable ecological impacts. Poorly managed storage temperatures, however, can compromise ground stability and infrastructure. Precautions must, therefore, be taken to anticipate these risks. Permafrost limits the use of BTES for thermal storage in northern regions, but RPTES presents a promising alternative. Studies show significant fuel savings and rapid returns on investment, with applications ranging from building heating to air management in mines. Northern greenhouses also benefit from these technologies, extending growing

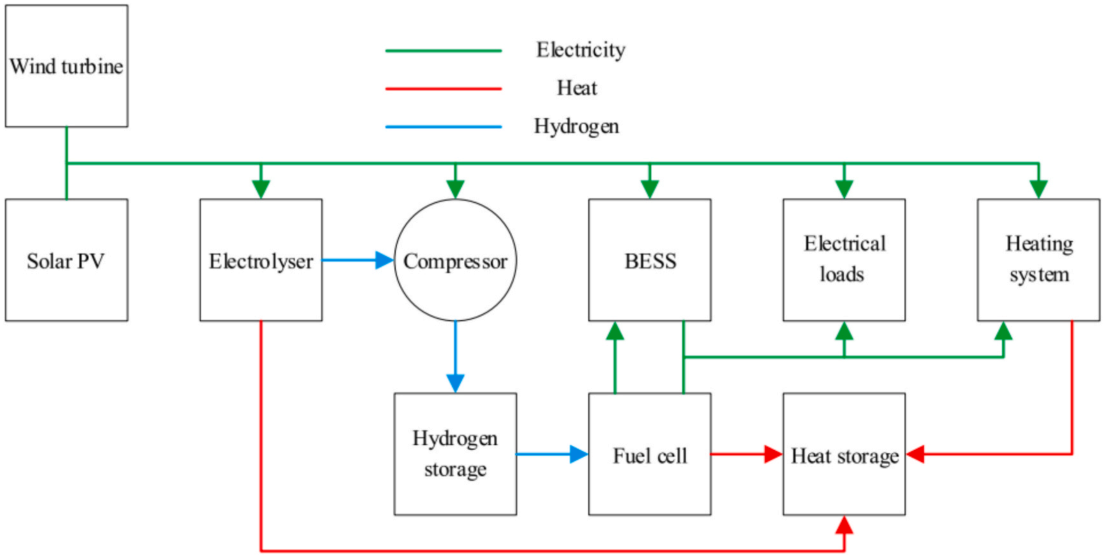


Fig. 10. Stand-alone hydrogen-based system, including waste heat recovery from the fuel cell and electrolyzer [166].

seasons through efficient heat storage.

Regarding PHES, while efficient and sustainable, this technology requires suitable sites, such as natural topographies or costly infrastructure. In northern regions, freezing temperatures and remoteness increase challenges, but solutions like using abandoned mines are being explored. However, in-depth studies are still needed to ensure the viability of such projects in isolated areas. In the northern context, studies conducted in locations such as Kangirsuk and Tuktoyaktuk show significant reductions in diesel consumption, reaching up to 63.4 %, through hybrid systems integrating CAES. However, CAES requires high initial investments. While it offers advantages over batteries or hydrogen in terms of cost, efficiency, and maintenance, further research is necessary to optimize its deployment in northern communities. On the other hand, FES appears suitable when combined with a battery system but cannot serve as a standalone storage solution.

Batteries have proven effective in reducing fossil fuel consumption in northern Canadian communities, though challenges related to extreme climatic conditions persist, particularly reduced performance in low temperatures. Despite their high cost, lithium-ion batteries are favored due to their high energy density, long lifespan, and low self-discharge rate. However, their cost remains prohibitive for large-scale applications, such as in remote mines, limiting widespread adoption. Thermal storage systems and PHES, on the other hand, with relatively lower costs and higher storage capacities, offer great potential, enabling the deployment of autonomous renewable energy systems in the mining sector [169,170]. Studies indicate that hydrogen provides a viable storage solution. However, standalone systems integrating hydrogen, while technically feasible, remain expensive. Hybrid wind-hydrogen systems are technically viable for large-scale projects like the Raglan mine. However, high technology and storage infrastructure costs constrain their profitability.

A promising but still unexplored storage solution for off-grid communities lies in integrating multi-energy pumped thermal storage (PTES) systems [171]. This innovative technology operates on the conversion principle between thermal and electrical energy. It stands out for its ability to store electricity while simultaneously recovering and delivering heat, making it particularly well-suited for isolated communities where heating, hot water, and electricity needs often coexist [172]. One of the key advantages of these systems is their geographic flexibility: they do not require pre-existing reservoirs, which positions them favorably compared to CAES and PHES, as they can be installed almost anywhere. Additionally, their lifespan is a significant advantage over current battery technologies.

Table 2 compares energy storage technologies based on their energy density, cost, efficiency, lifespan, and geographical dependence. CAES and PHES offer good energy density but are expensive per kWh stored and rely on specific geographic locations. FES has high efficiency but comes with a high cost per kW. Li-ion batteries provide higher efficiency and low geographical dependence, but their shorter lifespan leads to more frequent replacement costs. Hydrogen storage, while promising in energy density, is still limited by its high cost and moderate efficiency. Depending on local priorities, the choice of technology varies between sustainability, cost, and flexibility.

3. Conclusion

This study explores the challenges and opportunities associated with decarbonizing remote communities in northern Canada. These regions' heavy reliance on fossil fuels, particularly diesel, leads to significant greenhouse gas emissions, emphasizing the urgent need for sustainable energy solutions. The study assesses the landscape and potential of various renewable energy sources, such as wind, solar, and hydroelectricity, while identifying the technical, logistical, and social barriers to their implementation. It also reviews the current state of research and applications of different energy storage technologies in these communities, highlighting their benefits, drawbacks, and limitations. The main insights from this analysis are as follows:

- Wind energy is particularly effective in northern regions of Canada. When integrated into wind-diesel hybrid systems, it has shown the ability to significantly reduce diesel usage, lowering operational costs and greenhouse gas emissions.
- Photovoltaic panels, although less efficient in winter due to the short daylight hours and extreme temperatures, can still effectively complement other renewable energy sources. Solar panels help reduce fossil fuel consumption, particularly in summer, when sunlight is stronger.
- Hydroelectricity plays a major role in renewable energy production for off-grid communities in Canada. However, its development is limited by geographical factors. Additionally, the environmental impact of large dams and the disruption of ecosystems can pose further challenges, limiting its deployment in certain regions.
- Relying exclusively on a single renewable energy source is risky. While solar, wind, and hydroelectricity resources offer significant potential, each has inherent limitations, such as intermittency or geographic availability, which can compromise their long-term

Table 2
Comparison of electrical energy storage technologies (2020–2024), [,]

System	Energy density (kWh/m^3)	Cost ($/kWh)	($/kW)	Efficiency (%)	Lifespan (year)	Geographical dependence
PHES	0,5—1,5	5—100	300—2500	65—87	30—60	Yes
CAES	3—12	2—200	400—2250	40—95	20—60	Yes
FES	–	12—4500	1100–3000	80	–	No
Li-Ion B	300	500—2500	270—1500	85—95	5—15	No
Flow B	16—60	120—1000	175—10000	57—85	5—15	No
Hydrogen	500—3000	1—10	3500—10000	20—50	5—30	No
PTES	0,25—6,9	–	–	70—80	25—30	No

adapted from 173174.

reliability. Therefore, combining multiple renewable energy sources is key to ensuring stable and reliable production. Similarly, completely eliminating diesel generators within communities is difficult to achieve, particularly due to energy security concerns.

- Integrating Indigenous knowledge into energy management is essential for ensuring an energy transition that respects local traditions and lifestyles. Due to their close relationship with the land, Indigenous communities offer valuable perspectives in planning and developing energy projects. Their active participation helps create culturally appropriate solutions and strengthens the projects' acceptance and sustainability.
- Despite the extreme climatic conditions, thermal energy storage represents a key solution for northern regions as it allows for storing large amounts of energy. BTES, in particular, holds great potential but requires precautions to prevent soil degradation. RPTES systems have proven their value, and multi-energy PTES technologies also show promise, offering a reliable alternative to more traditional systems.
- CAES proves to be an interesting alternative despite its high initial cost. This system has the advantage of storing energy for long periods and on a large scale. PHES is another efficient technology, but its deployment depends on the presence of natural terrain features or the need to invest in expensive infrastructure. As for FES, while they are not suitable as a standalone storage technology, they can complement other systems, such as batteries, by providing fast and supplementary storage.
- Batteries, particularly lithium-ion batteries, have proven effective in reducing dependence on fossil fuels but face challenges in extreme climatic conditions, where their performance decreases in low temperatures. Their high cost remains a barrier. Hydrogen, on the other hand, offers a viable storage solution but is also limited by high costs.
- There is no one-size-fits-all solution to meet the energy needs of remote communities. Depending on local priorities, such as required power, storage capacity, sustainability, cost, or flexibility, the choice of technology must be tailored. Therefore, it is essential to combine multiple types of storage systems to effectively address the specific needs of each community.

In conclusion, decarbonizing remote communities in northern Canada requires a multifaceted approach combining various renewable energy sources and storage technologies. Given these regions' harsh environmental conditions and logistical challenges, relying on a single energy source would be insufficient. A hybrid model that integrates wind, solar, and hydroelectric power alongside advanced energy storage solutions can help ensure energy reliability and reduce dependence on fossil fuels. Moreover, integrating Indigenous knowledge and local priorities is crucial for creating culturally appropriate and sustainable energy systems. Indigenous communities possess valuable insights into the local environment and traditional practices that can enhance the effectiveness of energy solutions. By incorporating these perspectives into the planning and implementation process, energy systems will not only be more efficient but also more widely accepted, ensuring long-term sustainability and alignment with the community's values. One of the main challenges associated with the integration of renewable technologies and storage systems in remote northern Canadian communities lies in the definition and assessment of costs. Due to the pronounced geographic isolation of these areas and their particularly harsh climatic conditions, projects require specific technical and logistical adaptations that significantly complicate the development of reliable economic models. These specificities make it difficult to rigorously quantify the investments required, both for the installation and long-term operation of the infrastructure. This complexity highlights the need for a dedicated in-depth study focused on cost analysis in northern contexts, in order to better inform technological choices and the design of effective support policies.

CRediT authorship contribution statement

Sullivan Durand: Writing – original draft. **Patrick Turcotte:** Writing – review & editing. **Didier Haillot:** Writing – review & editing. **Daniel R. Rousse:** Writing – review & editing. **Hossein Arasteh:** Writing – review & editing. **Siba Kalivogui:** Writing – review & editing. **Kun Zhang:** Writing – review & editing. **Ricardo Izquierdo:** Writing – review & editing. **Abdelatif Merabtine:** Writing – review & editing. **Wahid Maref:** Writing – review & editing. **Adrian Ilinca:** Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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